ADA037214

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

12 NW

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DSL Technical Note 92	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) SCCU/MCCU Characteristics for Autodin II.		5. TYPE OF REPORT & PERIOD COVERED (9) Technical Note,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Vinton G. Cerf (12) 25p.		8. CONTRACT OR GRANT NUMBER(s) (15) MDA903-76C-0093, ARPA Order No. 2494
9. PERFORMING ORGANIZATION NAME AND ADDRESS Stanford Electronics Laboratories Stanford University Stanford, CA 94305		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 6T10
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency Information Processing Techniques Office 1400 Wilson Ave., Arlington, VA 22209		12. REPORT DATE (11) July 1976 13. NO. OF PAGES 22
14. MONITORING AGENCY NAME & ADDRESS (if diff. from Controlling Office) Mr. Philip Surra, Resident Representative Office of Naval Research Durand 165, Stanford University		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from report)

(14) DSL-TN-92

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Internetting, Computer Networks, Communication Protocols, Line Control Procedures, Multi-channel Control Unit, Single-Channel Control Unit, MCCU, SCCU, TCP, AUTODIN II

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This note considers the cost and performance of the Single-Channel and Multi-Channel Control Units (SCCU,MCCU) which could be used to connect host computers to the AUTODIN II network with little or no software modification to the attaching host. The SCCU provides a single switchable logical connection (possibly spanning more than the AUTODIN II network) to another host. The MCCU provides multiple, switchable connections. Results from the ARPANET internetting research project are used as a basis for this note.

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

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SCCU/MCCU CHARACTERISTICS FOR AUTODIN II

by

Vinton G. Cerf

July 1976

Technical Note 92

DIGITAL SYSTEMS LABORATORY

Dept. of Electrical Engineering   Dept. of Computer Science

Stanford University

Stanford, California

ABSTRACT

This note considers the cost and performance of the Single-Channel and Multi-Channel Control Units (SCCU,MCCU) which could be used to connect host computers to the AUTODIN II network with little or no software modification to the attaching host. The SCCU provides a single switchable logical connection (possibly spanning more than the AUTODIN II network) to another host. The MCCU provides multiple, switchable connections. Results from the ARPANET internetting research project are used as a basis for this note.

KEYWORDS

Internetting, Computer Networks, Communication Protocols, Line Control Procedures, Multi-channel Control Unit, Single-Channel Control Unit, MCCU, SCCU, TCP, AUTODIN II

This research was supported by the Defense Advanced Research Projects Agency under ARPA Order No. 2494, Contract No. MDA903-76C-0093

SCCU/MCCU Characteristics for Autodin II

1. Introduction

The purpose of this report is to characterize as accurately as our present knowledge will permit, the size, performance, and cost of the Single Channel and Multi-channel control units for the Autodin II [1] network. These units act as interfaces between the network and a host which wishes to use the network without making modification to its existing I/O facilities (or, at least, without making very significant modification to these facilities).

It is assumed that these units consist of three basic components:

(a) Segment Interface Protocol Program (SIP)

(b) Transmission Control Program (TCP)[2,3]

(c) Host Specific Interface (HSI)

At Stanford University's Digital Systems Laboratory (SU-DSL), we have engaged in a research program* to experiment with the TCP, its interface to several networks, and its interface to several user programs. The prototypical SCCU has been built on a Digital Equipment Corporation (DEC) LSI-11 (PDP-11/03) and interfaced to the ARPANET and the Packet Radio Network (a DARPA/IPTO research network using ground packet radio repeaters to provide the packet communication facility). The equivalent MCCU has been built for a DEC PDP-11/20 and has also been interfaced to the ARPANET over a Very Distant Host Interface [4, Appendix F]. Other versions of the MCCU have been built for the DEC PDP-10X [by Bolt Beranek and Newman (BBN)], and a DEC PDP-11/40 [also by BBN], as well as a DEC PDP-9 [by University College London].

Letterson File

* Sponsored by DARPA/IPTO under contract No. MDA903-76C-0093

A

The PDP-10 MCCU version runs under the TENEX operating system [5] and is written in BCPL [6,7], a high level, ALGOL-like block-structured language. Both the SU-DSL and BBN PDP-11 MCCU's are also written in BCPL and run under the ELF (8,9,10] operating system. The SU-DSL SCCU is written in MACN-11 [11], a macro-assembly language for the PDP-11.

At the time of this writing, all these systems were functioning experimentally, but there existed some implementation deficiencies which affected some of the performance measurements. We expect these problems to be remedied during the second quarter of 1976, and thus, the performance described herein can be taken as a lower bound rather than an upperbound.

2. The Single Channel Control Unit

2.1 Physical characteristics

At SU-DSL, an SCCU was constructed using a DEC LSI-11 system composed of:

1. LSI-11/03 CPU
2. 8K 16 bit RAM memory
3. DRV-11 8 bit general purpose full duplex interface
4. DLV-11 TTY interface
5. 8 bit 1822 HOST/IMP interface [built by SU-DSL, see reference 12]

The hardware cost of this configuration, including the 1822 interface, is approximately $3600. There is room in the configuration for an additional pair of double-height circuit boards which could be used, for instance, to add a floppy disk controller, or more memory, or an additional TTY interface [e.g. to allow for a combination of hardcopy and CRT devices at the SCCU workstation].

The 1822 interface is interrupt driven (for each 8-bit byte transferred in either direction) and is consequently not especially efficient (but it is small and cheap!). The interface has a maximum signalling bandwidth of 50kb/sec.

A DMA version of the 1822 interface is under development by Collins Radio Company; it will require more space (probably two double height circuit boards), but will probably achieve higher maximum bandwidth.

The SCCU at SU-DSL is configured as an inter-network terminal controller. It's software (all of which is written in the MACN-11 assembly language) includes a version of TCP called TCPØ [13] and a version of the standard ARPANET TELNET [14,15]. TCPØ conforms to all the standard TCP conventions in reference [2], except that

1. It manages only a single TCP-TCP connection.
2. It generates only single packet ARPANET messages (but will receive multipacket messages).
3. It does not reassemble fragmented segments
4. It responds to, but does not send Desynchronization requests [it need not do this, since it can always remember the last sequence number used on its previous connection].
5. It responds to, but does not send INTerrupts. [This will be remedied shortly, and is not expected to require much additional code].

The TELNET will only negotiate echo mode and "Go Ahead" character options, rejecting all others; aside from that, it implements the full basic TELNET. The table below illustrates the size of the various components of our SCCU. The size does not vary significantly for the ARPANET versus PRNET versions, but if the Station to Packet Repeater Protocol (SPP) [16] is required for PRNET access, the size may increase by as much as 1K words of code and buffer space.

C

As can be seen from Table I, the software to support a terminal using TCPØ and TELNET occupies slightly less than half the available space. Our performance measurements on this configuration indicate that it could reasonably support more than one terminal, or an RJE station. Of course, the SCCU is capable of supporting only a single TCP connection at a time. Since the TCPØ code is re-entrant, it could be used to support more than one connection. This would require an increase in "operating system" complexity [currently it manages two processes: input and output], and more buffer space. The author of the TCPØ estimates that, at worst, the code might double in size if general multiple connection service were to be supported. Assuming a comparable increase in buffer requirements for each new connection, we estimate that an MCCU version of the TCPØ/TELNET programs might occupy 5100 + n x 500 words, allowing up to five connections* in the 8K words of space available. These estimates are probably unduly pessimistic.

An SCCU which acts as a host interface to AUTODIN II will not contain the TELNET software. It's size is thus reduced by 1454 words to 2542 words, but the addition of SIP and Host specific software may bring the total back up to 4K or more. We believe that for single connection host support, the current configuration should be adequate, although we believe that a DMA 1822 interface would be appropriate to improve the basic bandwidth of the system.

In terms of programming effort, we estimate that the TCPØ required 3-6 man-months of effort (by an extremely capable systems programmer) and for the TELNET, about the same. A multi-connection version of TCPØ might require

* Assuming multiconnection TCPØ = 2700, OS + controllers + basic buffers = 1200, TELNET=1200 and 500 words of buffer and table per connection, "n" is the number of connections.

SCCU Software Configuration

(all sizes in decimal 16 bit words)

(a)	Interrupt vectors	128
(b)	Operating system (includes 40 words of stack space)	150
(c)	Buffers*	
	(1) input buffer	512
	(2) output buffer	128
	(3) reassembly buffer	190
	(4) retransmission buffer	190
	(5) TELNET buffers	80
(d)	1822 interface driver	113
(e)	TCB (connection status)	37
(f)	TCPØ program	1337
(g)	TELNET program and tables	1168
	TOTAL	3996

TABLE I

* Note: These buffers, though n <u>words</u> each, actually accommodate n bytes, owing to special control information about each byte which must be kept in the circular buffer.

6-12 man months of effort, but we haven't attempted to do this, so the estimate is subject to the usual doubts.

A complex SIP (e.g. the PRNET SPP [16]) might require an additional 6-12 man months, and a complex host interface, the same. We have not had experience with the programming of front-end types of interfaces. The UCL (University College London) PDP-9 interface to a 360/195 (standard ARPANET NCP, TELNET, and file transfer protocol (FTP) translated into ØS 360/RJE protocol) required on the order of 3 man years of effort. Our own FTP (for standard ARPANET application under ELF) was written in assembly language in about 3-6 man months.

We conclude that, starting from scratch, a full SCCU with relatively complex host and network interfaces might require from 15 to 30 man months of effort and for a multi-connection version of SCCU, perhaps a total of 18 to 36 man months. All these figures assume the programmers are of the quality one finds in the universities under the cognomen "hacker*."

2.2 SCCU Cost Estimates

The basic cost of the LSI-11 hardware in our SCCU is shown in Table II below. If the simple 1822 interface were to be replaced with a DMA version, we estimate that the cost would increase to about $4120 [$1,000 extra for the DMA 1822, dropping the DRV-11 and the SU-DSL 1822].

---

* Hacker: someone who would rather chase bugs in a computer program than almost anything else.

SU-DSL SCCU Cost

1.	LSI-11/03 + 4K memory + DLV-11 TTY	$2495
2.	DRV-11	195
3.	4K RAM memory	625
4.	SU-DSL 1822 interface	250 [est.]
	TOTAL	$3565

TABLE II

2.3 SCCU Performance Estimates

It is important to note two characteristics of the SU-DSL SCCU before considering its performance. First, the LSI-11/03 is quite slow; instructions may take 5-7 microseconds to complete. Second, the SU-DSL 1822 interface, while full duplex, requires interrupt service for every 8-bit byte that passes in or out of the LSI-11 memory. Consequently, the interrupt service loop constitutes a potential bottleneck in achievable bandwidth. This bottleneck could be remedied by the use of a DMA 1822 interface and/or a faster CPU.

Table III illustrates the full duplex bandwidth of the TCPØ, driven by a simple message generator, but utilizing an internal software loop, rather than passing out the 1822 interface and back in again. This gives an upperbound on the software speed of the TCPØ. All numbers are decimal, and those representing bandwidth are full-duplex (i.e. if the bandwidth is x bits/sec, then the input and output channels are each operating at x bits/sec).

There are two sets of measurements in Table III, the second and third columns show bandwidth for a self-looped* LSI-11 running TCPØ, and the fourth and fifth columns show the same measurements for TCPØ running on a PDP-11/20. Linear regression fitting produces equations (1) and (2), relating letter length and delay per letter. All figures are for real data bandwidth, exclusive of the TCP header overhead (or any lower level control overhead).

* Internal software loop in TCPØ.

Letter size (in bytes)	Letters per second (LSI-11)	Bits per second (LSI-11)	Letters per second (PDP-11/20)	Bits per second (PDP-11/20)
1	246.2	1970	377	3016
10	171.8	13745	257	20590
40	85.2	27248	124.5	39845
80	50.8	32480	73.5	47018
120	36.2	34768	52.3	50208

TCPØ Bandwidth

TABLE III

$$D_A(L) = 3.86 + .196L \text{ msec.} \qquad (1)$$

$$D_B(L) = 2.51 + .128L \text{ msec} \qquad (2)$$

where A = TCPØ on LSI-11/03

B = TCPØ on PDP-11/20

L = length of letter <u>text</u> in 8 bit bytes

D(L) = delay in milliseconds for letters of text length L

The ratio of $D_A(L)/D_B(L)$ tends, in the limit (for large L) to 1.42, which gives an approximate speed ratio of 1.4 to 1 in favor of the PDP-11/20. Comparable performance figures for the MCCU are given in the next section.

In Table IV, we show the effect of adding the 1822 interface, looping outgoing packets back to the LSI-11 SCCU. Interrupt processing occurs for each byte of incoming or outgoing data, so the achievable throughput drops dramatically. A DMA interface would not introduce nearly as much processing overhead. The second column, labeled "WINDOW" shows the effect of a 190 octet (byte) window, limiting the number of outstanding octets to that number. The maximum allowed ARPANET message was 214 bytes, so that text in excess of 178 bytes (there are 36 bytes of internet header which must be carried in the ARPANET message) will be put into several TCP internet packets. The third column, labeled "NO WINDOW" had a window constraint of 1300 bytes and an ARPANET message size limit in excess of 400 bytes. At letter sizes of 200, the maximum ARPANET message effect* is apparent, since additional TCP headers are required to carry the letter segments.

3 The Multi-Channel Control Unit

3.1 Physical Characteristics

In section 1, we made reference to several MCCU configurations at SU-DSL, BBN, and UCL. We also suggested in section 2 that the SCCU at SU-DSL might be upgraded to MCCU capability. We are only in a position to describe accurately our experiences with the TCP on our DEC PDP-11/20, and this section of the report will concentrate on this particular implementation. The SU-DSL TCP is written in BCPL, and is designed to run as a collection of processes under the ELF operating system.

---

* for the WINDOW case.

LSI-11 SCCU Bandwidth (with 1822 adaptor)

Letter size (in bytes)	WINDOW DATA RATE (letters/sec) [bits/sec]	NO WINDOW DATA RATE
1	73.1 [584]	73.3 [586]
10	59.2 [4735]	
20	48.2 [7719]	
40	35.2 [11277]	35.3 [11296]
60	27.7 [13308]	
80	20.4 [13082]	22.9 [14640]
160	10.4 [13333]	13.4 [17195]
200	7.8 [12440]	
240	6.9 [13312]	9.5 [18304]
320	5.2 [13355]	7.4 [18880]
400	4.1 [13093]	6.0 [19253]

TABLE IV

The physical characteristics of the SU-DSL PDP-11/20 are shown below:

1. PDP-11/20 CPU
2. 28K 16 bit words (12K core, 16K RAM)
3. ARPANET Very Distant Host Interface
4. PRNET DEC IMP-11A 1822 interface
5. KSR 33 control TTY
6. 2 dial-up modem ports (DC11's)
7. 2 hard-wired TTY ports (DC11's)
8. OMRON CRT terminal with 8K bytes of memory
9. Two DECTAPE units
10. 1 RS64 64K word fast drum
11. 1 Diablo 44 dual platter 5.6 byte disk

The very distant host interface is connected to the SUMEX IMP through a modem emulator [17] built at SU-DSL. This emulator is capable of speeds up to 50K bits/sec.

The software organization of the MCCU is shown below in Table V. The VDH RTP realizes a "reliable transmission protocol" for line control over the host/IMP modem channel. The Exerciser is a program which allows the creation of traffic sources and sinks to test TCP performance. The FLEA debugger is a useful tool both for debugging and for setting up unusual TCP test conditions.

A complete MCCU would probably not contain FLEA or the Exerciser. The ELF Kernel might be replaced by a simpler process manager. A host/MCCU interface would have to be included.

SU-DSL MCCU Software Configuration

(all figures in decimal 16 bit words)

(a)	free storage	1,900	words
(b)	ELF kernel	8,500	words
(c)	FLEA debugger	1,000	words
(d)	Exerciser	2,400	words
(e)	TCP system	13,000	words
(f)	VDH RTP	1,300	words
	TOTAL	28,100	words

TABLE V

According to the authors of the BCPL compiler for the PDP-11 [6,7], the space penalty for use of the higher level language is a factor of 2. Thus, reprogramming in assembly language might reduce the size of the TCP proper to about 7200 words. We note, also, that procedure calls with parameters are expensive in BCPL. The use of global variables and fewer procedure calls might further reduce the program to 6000 words or less. We have learned, from our BCPL exposure, that high level languages are sometimes tricky, owing to wide variations in the cost of some programming facilities.

We can estimate the approximate size of a general purpose MCCU. We will assume a much simpler operating system, and the recoding of the TCP in a more efficient manner. The Host specific interface and the MCCU/Autodin II interfaces we will assume are about as complex as the RTP. Table VI illustrates the breakdown.

Any reasonable MCCU ought to fit in a 32K word system, including substantial buffer storage.

For completeness, we illustrate in Table VII the software breakdown of the SU-DSL BCPL TCP.

It is quite clear that the incoming packet reception software is the bulkiest module. All error handling and much of the state changing for connection status occur in this module, accounting, in part, for its size.

3.2 MCCU Cost Estimates

Estimates for MCCU cost are made somewhat difficult because the choice of CPU depends on the bandwidth required by the host which the MCCU interfaces to Autodin II. Similarly, the HOST/MCCU interface cost may vary dramatically from a few hundred to several thousands of dollars. We can reasonably assume

General MCCU Software Configuration

(all figures in decimal 16 bit words)

(a)	free storage	16000
(b)	operating system	4000
(c)	TCP	6000
(d)	Host specific interface	2000
(e)	Autodin II interface	2000
	TOTAL	30000

TABLE VI

BCPL TCP Organization

(all figures in decimal 16 bit words)

(a)	Initialization code	203
(b)	Service routines	1583
(c)	User interfaces	1849
(d)	Letter sending	1490
(e)	Letter reception	987
(f)	Packet reception	3726
(g)	Packet retransmission	1007
(h)	ELF interfaces	1253
(i)	Network interface	900
	TOTAL	13000

TABLE VII

DMA channels from host/MCCU and MCCU/network. Memory costs are estimated at $.01/bit. CPU cost is based on LSI-11/03 technology. Table VIII shows the details. Even doubling the CPU cost leaves the total under $15,000.

3.3 MCCU Performance

Our performance measurements on the SU-DSL TCP are quite revealing. The introduction of VDH and IMP processing delays have a significant impact on performance. We made a series of three bandwidth tests which, within the (serious) limitations of our free buffer storage, pushed the system to its capacity. In table IX, we illustrate the results for three configurations:

(a) Internal TCP software loop

(b) VDH modem loop (corresponds to the TCPØ 1822 loop test results)

(c) IMP loop (TCP sends packets to itself through the IMP).

The TCP parameters were adjusted so that maximum length ARPANET messages were permitted [up to 8000 bits of text], and the flow control window was opened to permit up to 2048 bytes to be in transit at one time. The column labeled "SENDS outstanding" indicates how many letters ahead the transmit side is permitted to get before requiring an acknowledgment that a SEND is done. The "RECEIVES outstanding" indicates whether double input buffering is in effect. The bandwidth figures for bits/second refer to data only, not overhead bits for header, line control, etc.

It is evident that our implementation of the VDH reliable transmission protocol introduces substantial delay and consequently reduces throughput [In our implementation, the TCP interface to the RTP blocks until the ARPANET message (enclosing the TCP internet packet) has been sent out the line. This introduces substantial idle time during which the TCP sending side is blocked. We are rewriting this interface to eliminate the effect].

(Revised July 10, 1976)

GENERAL MCCU COST ESTIMATE

1.	LSI-11/03 + 4K memory + DLV-11	$2500
2.	Additional 24K memory	3750
3.	16 bit DMA host interface	1000
4.	16 bit DMA parallel/serial modem interface	5000
	TOTAL	$12,250

TABLE VIII

TCP BANDWIDTH TESTS

Letter Size in bytes	SEND outstanding	RECEIVES outstanding	IMP LOOP letters/sec [bits/sec]	VDH LOOP letters/sec [bits/sec]	TCP LOOP letters/sec [bits/sec]
1	15	2	7.5 [60]	11.5 [92]	--
1	10	2	7.7 [62]	10.2 [82]	14.8 [118]
10	10	2	8.0 [640]	7.2 [576]	18.1 [1448]
40	10	2	7.1 [2272]	8.3 [2656]	13.3 [4256]
80	10	2	6.9 [4352]	9.9 [6336]	--
80	8	2	--	9.0 [5760]	--
80	5	2	--	6.4 [4096]	12.7 [8128]
120	8	2	5.0 [4800]	--	--
120	5	2	--	6.3 [6048]	12.4 [11,904]
160	4	2	4.3 [5504]	5.4 [6912]	15.2 [19,456]
200	4	2	4.5 [7200]	6.0 [9600]	11.1 [17,760]
200	3	2	--	6.9 [11040]	14.8 [23,680]
200	2	2	--	6.3 [10,080]	12.9 [20,640]
300	3	2	3.8 [9120]	5.5 [13,200]	13.4 [32,160]
300	3	1	3.3 [7920]	--	--
400	2	1	2.7 [8640]	4.0 [12,400]	9.9 [31,680]
400	1	1	1.7 [5440]	--	--

TABLE IX

* Adding the IMP into the loop clearly introduces additional delay for the RTP. Since the RTP only uses a "WINDOW" of 2 packets (two logical channels), any delay for acknowledgment from the IMP can lead to blocking of the RTP channel. We plan to revise the TCP/RTP interface to be asynchronous and non-blocking to obtain better TCP/RTP overlap. One hopes that the ADCCP line control procedure will allow a sufficient number of outstanding packets (say 8-16) to avoid the possibility of bottlenecking.

4.0 Conclusions

Although we have not stressed the point in this note, the TCP system is extremely robust, able to recover from network failures and even the crash of a remote host. It is able to "clean-up" half-open connections which it discovers, if it should crash and later attempt to re-establish the connection.

The dollar cost of building SCCU's and MCCU's for Autodin II appears very modest. Our performance analyses indicate that any interface to Autodin II should employ DMA techniques, and that the line control procedure between the SCCU [MCCU] and the host [Autodin II Packet Switch] should allow ample number of outstanding packets [segments] to overcome local processing delays.

The implementation of the MCCU, if done in a higher level language, such as BCPL, PASCAL, will require great care, to avoid some of the unexpected overhead of higher level language compilation.

* Revised July 10, 1976

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Mr. Louis Pouzin
Mr. Hubert Zimmerman

Information Sciences Institute
University of Southern California
4676 Admiralty Way
Marina del Rey, CA 90291

Mr. Steven D. Crocker
Mr. Keith Uncapher

London, University College

Prof. Peter Kirstein
University College London
Department of Statistics &
Computer Science
43 Gordon Square
London WC1H OPD, England

Massachusetts Institute of Technology

Dr. J. C. R. Licklider
MIT
Project MAC - PTD
545 Technology Square
Cambridge, MA 02139

Mitre Corporation

Mr. Michael A. Padlipsky
MITRE Corporation
P. O. Box 208
Bedford, MA 01730

Network Analysis Corporation
Beechwood, Old Tappan Road
Glen Cove, New York 11542

Mr. Wushow Chou
Mr. Howard Frank

National Bureau of Standards

Mr. Robert P. Blanc
National Bureau of Standards
Institute for Computer Sciences
and Technology
Washington, D. C. 20234

Mr. Ira W. Cotton
National Bureau of Standards
Building 225, Room B216
Washington, D. C. 20234

National Physical Laboratory
Computer Science Division
Teddington, Middlesex, England TW11 OLW

Mr. Derek Barber
Dr. Donald Davies
Mr. Roger Scantlebury
Mr. P. Wilkinson

National Security Agency
9800 Savage Road
Ft. Meade, MD 20755

Mr. Dan Edwards
Mr. Ray McFarland

Norwegian Defense Research Establishment
P. O. Box 25
2007 Kjeller, Norway

Mr. Yngvar G. Lundh
Mr. P. Spilling

Oslo, University of

Prof. Dag Belsnes
EDB-Sentret
University of Oslo
Postbox 1059
Blindern, Oslo 3, Norway

Rand Corporation
1700 Main Street
Santa Monica, CA 90406

Mr. S. Gaines
Dr. Carl Sunshine

Rennes, University of

M. Gerard LeLann
Reseau CYCLADES
U.E.R. d'Informatique
B. P. 25A
35031-Rennes-Cedex, France

Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, CA 94025

Ms. E. J. Feinler
Augmentation Research Center

Dr. Jon Postel (4 copies)
Augmentation Research Center

Mr. D. Nielson, Director
Telecommunication Sciences Center

Dr. David Retz
Telecommunication Sciences Center

System Development Corporation

Dr. G. D. Cole
System Development Corporation
2500 Colorado Avenue
Santa Monica, CA 90406

Telenet Communications, Inc.
1666 K Street, N. W.
Washington, D. C. 20006

Dr. Holger Opderbeck
Dr. Lawrence G. Roberts
Dr. Barry Wessler

Defense Communication Agency

Dr. Franklin Kuo
4819 Reservoir Drive
Washington, D. C. 20007

Xerox Palo Alto Research Center
3333 Coyoto Hill Road
Palo Alto, CA 94304

Mr. David Boggs
Dr. R. Metcalfe
Mr. John Shoch
Dr. William R. Sutherland

Stanford University

Mr. Ronald Crane, Digital Systems Laboratory
Mr. Yogen Dalal " " "
Ms. Judith Estrin " " "
Prof. Michael Flynn " " "
Mr. Richard Karp " " "
Dr. John Linvill, Electrical Engineering
Mr. James Mathis, Digital Systems Laboratory
Mr. Darryl Rubin " " "
Mr. Wayne Warren " " "

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BELL LABORATORIES

Dr. Elliot N. Pinson, Head
Computer Systems Research Department
Bell Laboratories
600 Mountain Avenue
Murray Hill, New Jersey 07974

Dr. Mark Rochkind
Bell Laboratories
600 Mountain Avenue
Murray Hill, New Jersey 07974

Mr. Kenneth L. Thompson
1103 High Court
Berkeley, California 94708

B N R, Inc.

Mr. Alex Curran, President
B N R, Inc.
3174 Porter Drive
Palo Alto, California 94304

Mr. Barry Gordon
B N R, Inc.
3174 Porter Drive
Palo Alto, California 94304

Mr. Alan Chapman
B N R, Inc.
3174 Porter Drive
Palo Alto, California 94304

BURROUGHS CORPORATION

Dr. Wayne T. Wilner
Burroughs Corporation
3978 Sorrento Valley Boulevard
San Diego, California 92121

Mr. John Mazola
Burroughs Corporation
25725 Jeronimo Road
Mission Viejo, California 92675

Mr. Louis de Bartelo
Burroughs Corporation
1671 Reynolds
Irvine, California 92714

GENERAL ELECTRIC COMPANY

Dr. Richard L. Shuey
General Lectric Research and
Development Center
P.O. Box 8
Schenectady, New York 12301

Mr. J. T. Duane, Manager
Special Purpose Computing Center
General Electric Company
1285 Boston Avenue
Bridgeport, Connecticut 06602

Mr. Ronald S. Taylor
General Electric Company
175 Curtner Avenue
San Jose, California 95125

GENERAL MOTORS CORPORATION

Dr. George C. Dodd, Assistant Head
Computer Science Department
General Motors Research Laboratories
General Motors Technical Center
Warren, Michigan 48090

Dr. Joseph T. Olsztyn
Computer Science Department
General Motors Research Laboratories
General Motors Technical Center
Warren, Michigan 48090

Dr. James Thomas
Computer Science Department
General Motors Research Laboratories
General Motors Technical Center
Warren, Michigan 48090

HEWLETT-PACKARD

Mr. Don Senzig
Hewlett-Packard Laboratories
Building 18
1501 Page Mill Road
Palo Alto, California 94304

Dr. J. R. Duley
HPL/ERL
3500 Deer Creek Road
Palo Alto, California 94304

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HEWLETT-PACKARD (continued)

Mr. Stephen Walther
HPL/ERL
3500 Deer Creek Road
Palo Alto, California 94304

HUGHES AIRCRAFT COMPANY

Mr. R. Eugene Allen
Hughes Aircraft Company
Bldg. 604, M.S. D-222
P.O. Box 3310
Fullerton, California 92634

Mr. Thomas J. Burns
Hughes Aircraft Company
Bldg. 390, M.S. 2007
P.O. Box 92919
Los Angeles, California 90009

Hughes Aircraft Company
Attn: B. W. Campbell 6/E110
Company Technical Documents Center
Centinela and Teale Streets
Culver City, California 90230

IBM

Dr. Leonard Y. Liu, Manager
Computer Science
International Business Machines Corporation
K51-282, 5600 Cottle Road
San Jose, California 95193

Mr. Harry Reinstein
International Business Machines Corporation
1501 California Avenue
Palo Alto, California 94303

Dr. Donald Frazer
IBM Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

MICROTECHNOLOGY CORPORATION

Mr. Fred Buelow
Microtechnology Corporation
224 N. Wolfe Road
Sunnyvale, California 94086

Mr. Naoya Ukai
Microtechnology Corporation
224 N. Wolfe Road
Sunnyvale, California 94086

Mr. John J. Zasio
Microtechnology Corporation
224 N. Wolfe Road
Sunnyvale, California 94086

SIEMENS AG

Mr. Dr. Jan Witt
Siemens AG
Zentrale Forschung und Entwicklung
FL SAR
Hofmannstr. 51
8000 München 70, Germany

Mr. Harold Fritzsche
Siemens AG
Zentrale Fertigungsaufgaben
FTE 3 Aut 2
Schertlinstr. 8
8000 München 70, Germany

Mr. Volker Haberland
Siemens AG
Zentrale Fertigungsaufgaben
FTE 3 Aut 23
Schertlinstr. 8
8000 München 70, Germany

XEROX CORPORATION

Dr. Jerome Elkind, Manager
Computer Science Laboratory
Xerox Corporation
Palo Alto Research Center
3180 Porter Drive
Palo Alto, California 94303

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(continued)

XEROX CORPORATION (continued)

Mr. Robert Taylor, Principal Scientist
Computer Science Laboratory
Xerox Corporation
Palo Alto Research Center
3180 Porter Drive
Palo Alto, California 94303

Dr. Butler Lampson
Xerox Corporation
Palo Alto Research Center
3180 Porter Drive
Palo Alto, California 94303

STANFORD UNIVERSITY

Professor Edward J. McCluskey (2)
Director, Digital Systems Laboratory

Computer Science Department

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